

# Propeller effect in action in the ultraluminous accreting magnetar M82 X-2

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## ABSTRACT

We present here the first convincing observational manifestation of a magnetar-like magnetic field in an accreting neutron star in binary system – the first pulsating ultra-luminous X-ray source X-2 in the galaxy M82. Using the *Chandra* X-ray observatory data we show that the source exhibit the bimodal distribution of the luminosity with two well-defined peaks separated by a factor of 40. This behaviour can be interpreted as the action of the “propeller regime” of accretion. The onset of the propeller in a 1.37 s pulsar at luminosity of  $\sim 10^{40}$  erg s<sup>−1</sup> implies the dipole component of the neutron star magnetic field of  $\sim 10^{14}$  G.

**Key words:** accretion, accretion discs – magnetic fields – stars: individual: M82 X-2 – stars: magnetars – X-rays: binaries.

## 1 INTRODUCTION

The revolutionary discovery of the pulsating ultra-luminous X-ray source (ULX) X-2 in the galaxy M82 (known also as X42.3+59; Kaaret et al. 2006) made by the *NuSTAR* observatory (Bachetti et al. 2014) brought more questions than answers on the physics of accretion onto magnetized neutron stars as well as on the nature of ULXs. The chief distinction of this source is an extremely high luminosity for an accreting neutron star of about  $10^{40}$  erg s<sup>−1</sup>. Other parameters of the system, such as the spin period of  $P = 1.37$  s, the orbital period of 2.5 d and the companion star of  $5.2 M_{\odot}$  (Bachetti et al. 2014), are quite typical for an accretion powered X-ray pulsar in a high-mass X-ray binary. The variable over the *NuSTAR* observations spin-up was also detected with an averaged rate  $\dot{P} \simeq -2 \times 10^{-10}$  s s<sup>−1</sup>.

Exceeding the Eddington luminosity by almost two orders of magnitude is a challenge for current theories and imposes strong limitations on the physical conditions in the emitting region. Many different models are already proposed aiming at the understanding of the nature of this source. These models can be divided into two main groups depending on the neutron star magnetic field. One of the possibilities to emit such a high flux is to assume a magnetar-like magnetic field of the order of  $10^{14}$  G to significantly

reduce the interaction cross-section between radiation and the infalling material (see, e.g., Harding & Lai 2006). However, such a magnetic field is almost two orders of magnitude higher than the typical value observed in X-ray pulsars (Walter et al. 2015) and cannot be probed through spectral analysis. Therefore, all conclusions made so far are done based on the timing properties of M82 X-2. Particularly, assuming torque equilibrium, Ekşi et al. (2015) got the  $B$ -field strength of  $(2 \div 7) \times 10^{13}$  G. Dall’Osso et al. (2015) favoured a lower magnetic field of  $B \sim 10^{13}$  G, solving the torque equation numerically.

At the same time other authors declare a low magnetic field in M82 X-2 based on the same timing properties of the source. For instance, Kluźniak & Lasota (2015) argue that the observed torque is consistent with the accretion disc extending down to the vicinity of the neutron star surface. This can be the case only if the dipole magnetic field of the star is low,  $B \lesssim 10^9$  G. In the original paper by Bachetti et al. (2014), the magnetic field of the order of  $10^{12}$  G was estimated under the assumptions of the spin equilibrium and the Eddington accretion rate.

Thus, the lack of an obvious observational manifestation of the strong magnetic field precludes from any final conclusion. Here, using the *Chandra* observatory data, we show that the ULX M82 X-2 regularly enters the “propeller regime” of accretion which is seen as dramatic variations of the emitted luminosity. These observations imply the dipole

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**Table 1.** *Chandra* observations of ULX M82 X-2.

Obs Id	Instrument	Date (MJD)	Exposure (ks)	Pile-up fraction (per cent)	$\alpha$	Photon index	Luminosity <sup>a</sup> ( $10^{38}$ erg s <sup>-1</sup> )
361	ACIS-I	51441.474	33.25	1	-	$2.1 \pm 0.4$	$2.6 \pm 0.5$
1302	ACIS-I	51441.883	15.52	1	-	$1.3 \pm 0.7$	$2.0 \pm 0.6$
1411_000	HRC	51479.184	36.04	-	-	$0.4 \pm 1.2$	$114.3 \pm 11.3$
1411_002	HRC	51563.619	17.61	-	-	$1.35^b$	$1.7 \pm 1.0$
2933	ACIS-S	52443.784	18.03	20	$0.24 \pm 0.21$	$1.4 \pm 0.2$	$60.9 \pm 5.4$
5644	ACIS-S	53599.038	68.14	5	-	$1.4 \pm 0.1$	$107.4 \pm 3.4$
6361	ACIS-S	53600.664	17.45	5	-	$1.3 \pm 0.1$	$105.1 \pm 3.3$
8189	HRC	54109.345	61.29	-	-	$1.35^b$	$3.2 \pm 1.7$
8505	HRC	54112.093	83.22	-	-	$1.35^b$	$3.4 \pm 1.5$
10542	ACIS-S	55006.163	118.61	1	-	$1.0 \pm 0.2$	$3.8 \pm 0.4$
10543	ACIS-S	55013.936	118.45	1	-	$0.7 \pm 0.4$	$2.3 \pm 0.4$
11104	ACIS-S	55364.136	9.92	30	$0.39 \pm 0.09$	$1.1 \pm 0.2$	$119.5 \pm 9.6$
13796	ACIS-S	56148.648	19.81	30	$0.23 \pm 0.11$	$1.1 \pm 0.1$	$173.8 \pm 18.4$
15616	ACIS-S	56347.964	2.04	5	-	$1.35^b$	$6.4 \pm 2.3$
16580	ACIS-S	56691.841	46.85	30	$0.43 \pm 0.23$	$1.2 \pm 0.1$	$187.4 \pm 24.4$

<sup>a</sup> Luminosity in the 0.5–10 keV energy range corrected for interstellar absorption and assuming distance to the source  $D = 3.3$  Mpc (Foley et al. 2014).

<sup>b</sup> Fixed at the averaged value obtained in the bright observations least affected by the pile-up effect (Obs ID 5644 and 6361).

component of the neutron star magnetic field of  $\sim 10^{14}$  G, independently confirming the magnetar nature of this ULX.

## 2 CHANDRA OBSERVATIONS AND RESULTS

The *Chandra* X-ray observatory monitored the galaxy M82 more or less evenly during the past  $\sim 15$  years resulting in 29 publicly available observations. Some of them were pointed quite far from the ultra-luminous X-ray source M82 X-2. For our analysis, we selected only on-axis observations where the PSF shape allowed us to confidently separate the flux from M82 X-2 from the nearby sources. To exclude the selection bias we checked that none of the observations was triggered on a particular state of this source. The final sample of the utilized observations consisting of 15 pointings is listed in Table 1, where observation Id, name of the instrument, date and exposure of observation, as well as pile-up fraction are given. The level of pile-up was estimated using the CIAO tool PILEUP\_MAP, which calculates an average number of counts per ACIS frame. These numbers were then used to estimate the pile-up fraction.<sup>1</sup>

The reduction of the data has been done following the standard pipeline in the Chandra Interactive Analysis of Observations software package (CIAO, version 4.7). The source flux was estimated from the energy spectrum extracted using CIAO SPEXTRACT tool from a circular region of radius  $\sim 1''$ . The background was extracted from an annulus region centered at the source position with the inner and outer radii  $1''.8$  and  $7''.0$ , correspondingly. All contaminating point sources were excluded.

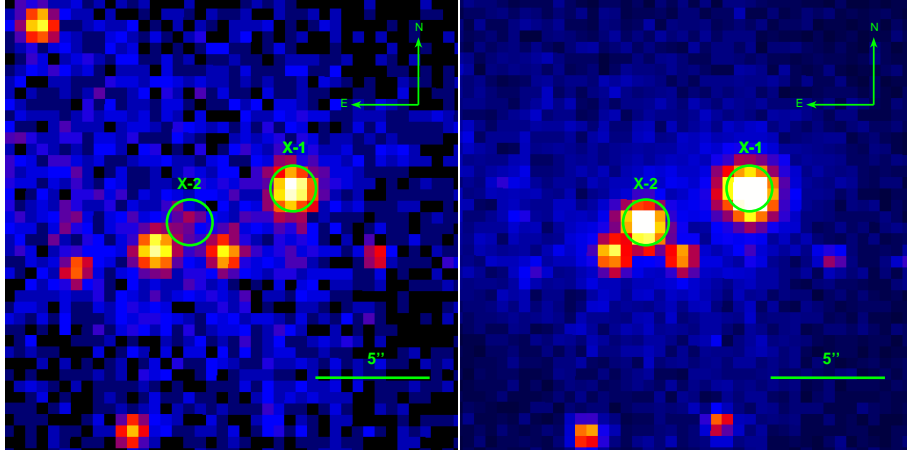
Spectral fitting was performed with XSPEC v. 12.8.1g (Arnaud 1996) using a simple power-law model with interstellar absorption (PHABS model). Spectra were grouped to have a minimum of 1 count per bin and the Cash statistic

was used. Some observations in the high-luminosity state suffer from the effect of pile-up with a pile-up fraction around 30 per cent at worse. This makes a reliable spectral fitting difficult, also taking into account the photon index and absorption values degeneracy in the *Chandra* energy band. The same is valid for low-luminosity states where we do not have enough counts to constrain spectral parameters independently. To solve this problem, we have selected observations in bright states which are much less affected by pile-up (Obs ID 5644 and 6361) and obtained the value of the hydrogen column density,  $N_H = 3.11 \times 10^{22}$  cm<sup>-2</sup>, and used this value to fit all remaining spectra allowing only the photon index and normalization to vary. Such an approach is supported by the recent work by Brightman et al. (2015) where a detailed spectral study of M82 X-2 was performed and no significant variability of  $N_H$  and  $\Gamma$  values between different *Chandra* observations was found. Additionally we checked the consistency of the spectral shape in different intensity states by the simultaneous fitting of all spectra obtained in the low state. The resulting spectral parameters are in very good agreement with ones in the bright state. For fitting the piled up spectra from observations with the pile-up fraction higher than 5% we followed the *Chandra* ABC guide to pile-up,<sup>1</sup> namely we added the PILEUP model (see also Brightman et al. 2015). The best-fit  $\alpha$  parameter, characterizing the grade morphing, as well as the photon index are shown in the Table 1.

The flux value and its  $1\sigma$  uncertainty were calculated using CFLUX model from the XSPEC package with the fixed hydrogen column density value. The resulting luminosity in the energy range 0.5–10 keV corrected for the absorption is shown in the Table 1. The luminosities of M82 X-2 measured by us are in a reasonable agreement with the recent results by Brightman et al. (2015), especially if one takes into account the density of point sources and the presence of the diffuse emission in the region around X-2 (see Fig. 1).

In order to estimate the bolometric flux, we assumed

<sup>1</sup> [http://cxc.harvard.edu/ciao/download/doc/pileup\\_abc.pdf](http://cxc.harvard.edu/ciao/download/doc/pileup_abc.pdf)



**Figure 1.** *Chandra* images of M82 galaxy’s centre during observations performed on September 20, 1999 (MJD 51441.47) when M82 X-2 was in a low-luminosity state (left) and August 17, 2005 (MJD 53599.04) when it was in a high-luminosity state (right). Circles indicate the positions of M82 X-1 and X-2 ultra-luminous X-ray sources.

the spectral shape of M82 X-2 to be typical to that of X-ray pulsars (power law modified by a high-energy cut-off at  $\sim 15$  keV with folding energy  $\sim 15$  keV; see, e.g., [Filippova et al. 2005](#)), resulting in a bolometric correction factor of 2. This factor is consistent with the broadband spectrum of the pulsed emission from M82 X-2 as seen by *NuSTAR* ([Brightman et al. 2015](#)).

The light curve of M82 X-2 as observed by *Chandra* is shown in Fig. 2(a). The histogram of the luminosities shown in Fig. 2(b) clearly demonstrates a bimodality, with two well defined peaks at  $\sim 1.0 \times 10^{40}$  erg s $^{-1}$  and  $\sim 2.8 \times 10^{38}$  erg s $^{-1}$ .<sup>2</sup> We stress here, that in the majority of low-luminosity states the source is still presented in the *Chandra* images. This can be illustrated by Fig. 1, where the maps of the central part of the galaxy M82 are shown in both “high” and “low” states.

### 3 DISCUSSION

#### 3.1 “Propeller” effect

The remarkable behaviour of M82 X-2 showing dramatic switches in luminosity by a factor of 40 can be interpreted as the onset of the so-called “propeller effect” ([Illarionov & Sunyaev 1975](#)). This effect is caused by a substantial centrifugal barrier which have to be broken by the infalling matter during the accretion onto the rotating neutron star with strong magnetic field. At the magnetospheric radius where the magnetic pressure equals the ram pressure of the infalling material, the accreting matter from a disc or a wind is “frozen” into the stellar magnetic field lines and rotates rigidly with the angular velocity of the star. The matter will fall onto the neutron star only if the velocity of the magnetic field lines at the magnetospheric radius is lower

than the local Keplerian velocity. Otherwise, the matter will be stopped at the radius of magnetosphere or even expelled from the system. Given the fact that magnetospheric radius depends only on the mass accretion rate and the strength of the magnetic field, the latter can be directly estimated if the propeller regime is observed in an accreting magnetized neutron star.

The threshold value of accretion luminosity  $L_{\text{lim}}(R)$  for the onset of the propeller can be estimated by equating the co-rotation radius (where a Keplerian orbit co-rotates with the neutron star)

$$R_c = \left( \frac{GM P^2}{4\pi^2} \right)^{1/3} \quad (1)$$

to the magnetospheric radius

$$R_m = k \dot{M}^{-2/7} \mu^{4/7} (2GM)^{-1/7}. \quad (2)$$

Here  $M$  is the neutron star mass,  $P$  its rotational period,  $\mu = BR^3/2$  is the magnetic dipole moment related to the surface polar dipole magnetic field strength  $B$  and the neutron star radius  $R$ , and  $\dot{M}$  is the mass accretion rate onto the neutron star. The dimensionless factor  $k$  relates the magnetospheric radius to the Alfvén radius computed for spherical accretion; for disc accretion it is usually taken  $k = 0.5$  ([Ghosh & Lamb 1978](#)). At the limiting accretion rate  $\dot{M} = \dot{M}_{\text{lim}}$ ,  $R_c = R_m$ , and the accretion luminosity is ([Campana et al. 2002](#))

$$L_{\text{lim}}(R) \simeq \frac{GM \dot{M}_{\text{lim}}}{R} \simeq 4 \times 10^{37} k^{7/2} B_{12}^2 P^{-7/3} M_{1.4}^{-2/3} R_6^5 \text{ erg s}^{-1}, \quad (3)$$

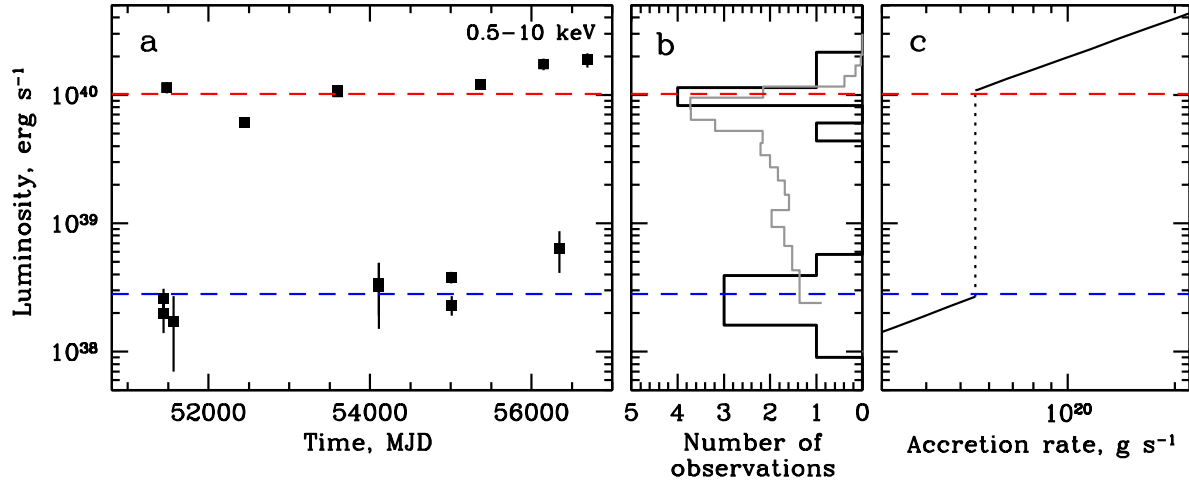
where  $M_{1.4}$  is the neutron star mass in units of  $1.4M_\odot$ ,  $R_6$  is neutron star radius in units of  $10^6$  cm,  $B_{12}$  is the magnetic field strength in units of  $10^{12}$  G.

The decrease of the accretion rate below  $\dot{M}_{\text{lim}}$  will lead to the propeller regime of accretion. The accretion efficiency drops significantly and the luminosity in that regime corresponds to the accretion onto the magnetosphere with the maximum value of ([Corbet 1996](#))

$$L_{\text{lim}}(R_c) = \frac{GM \dot{M}_{\text{lim}}}{R_c} = L_{\text{lim}}(R) \frac{R}{R_c}. \quad (4)$$

Thus if the pulsar is close to the spin-equilibrium, when

<sup>2</sup> The over-all bimodal flux distribution is confirmed by Fig. 3 from [Brightman et al. \(2015\)](#). The only flux measurement there fallen between the two states is the *Chandra* observation 10545 (MJD 55405), where the PSF of M82 X-2 is clearly blended with a nearby source, and hence is missing in our list of observations.



**Figure 2.** (a) Light curve of M82 X-2 obtained by the *Chandra* observatory during 15 years of observations. Luminosities are corrected for the absorption and given in the energy range 0.5–10 keV; (b) Distribution of individual observations over luminosities (black line). Bimodal structure is clearly seen. Red and blue dashed lines show the averaged luminosities in the “high” and “low” states, respectively. Grey line represents rescaled distribution of luminosities of X-ray pulsar LMC X-4 from the *Swift*/BAT data; (c) Predicted dependence of the magnetised neutron star luminosity on the mass accretion rate for the following parameters: spin period  $P = 1.37$  s, magnetic field strength  $B = 1.1 \times 10^{14}$  G, neutron star mass  $M = 1.4M_{\odot}$  and radius  $R = 10$  km, magnetospheric radius in units of the Alfvénic one  $k = 0.5$ . A small fraction (2.5 per cent) of the accreting material is assumed to leak through the magnetosphere onto the neutron star surface.

$R_c \approx R_m$ , small variations in the accretion rate will lead to large variations in the observed luminosity:

$$\frac{L_{\text{lim}}(R)}{L_{\text{lim}}(R_c)} = \left( \frac{GMP^2}{4\pi^2 R^3} \right)^{1/3} \simeq 170 P^{2/3} M_{1.4}^{1/3} R_6^{-1}. \quad (5)$$

Exactly such behaviour, i.e. abrupt switches between two intensity states, is observed in M82 X-2 (see Fig. 2(b)). To our knowledge none of the known other variability mechanisms would result in such a sharp bimodal distribution of flux from an accreting magnetized neutron star. For a comparison, we show in Fig. 2(b) by grey line the luminosity distribution for the X-ray pulsar LMC X-4 demonstrating a well established super-orbital variability as seen by the *Swift*/BAT all-sky monitor.<sup>3</sup> The variability patterns obviously differ much. This is also true for other sources with periodic (SMC X-1, Her X-1) and non-periodic (e.g., Cen X-3) variability of the flux. Unfortunately, the relatively short exposures of the *Chandra* observations do not permit us to detect transitions from one state to another. However, a quite dense observational program of M82 allows us to put an upper limit on the duration of such transitions: two observations separated by  $\sim 37.3$  days (ObsID 1302 and 1411\_000) show flux change by a factor of  $\sim 50$ .

### 3.2 Magnetic field measurement

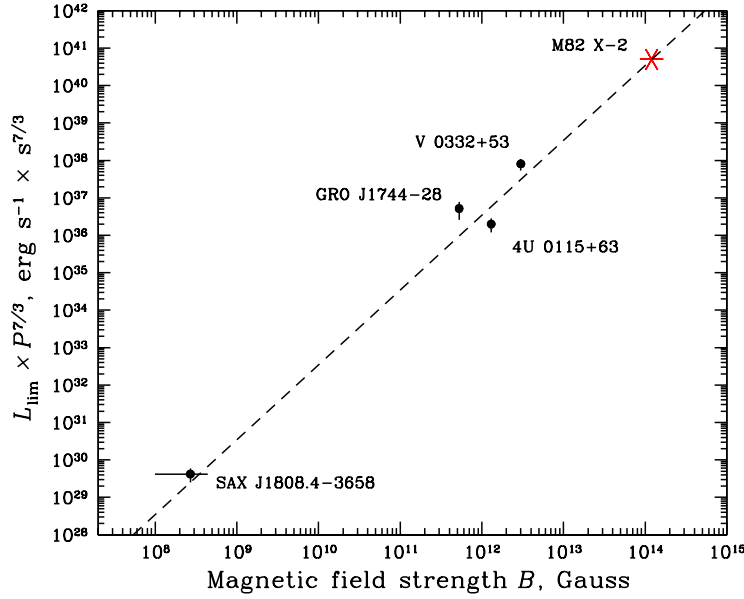
Theoretically, expressions (3)–(5) would allow us to measure the magnetic field of the neutron star together with its com-

pactness. However, the source does not follow the theory so closely. Indeed, the observed ratio of luminosities in “high” and “low” states is 40, that is smaller than the ratio around 210 predicted by equation (5) for a given pulse period, probably because of a substantial leakage of accreting material through the magnetosphere. Such a behaviour is typical for accreting X-ray pulsars (Doroshenko et al. 2011, 2014). This is also supported by the fact that we do not detect significant changes of the source spectra in the two states. The jump by a factor of 40 in the luminosity can be easily explained if 2–3 per cent of accreting matter leaks through the magnetosphere (see Fig. 2c).

However, the limiting luminosity in the high state is less affected by such uncertainties in the accretion model and can be used to estimate the magnetic field strength of the neutron star directly from equation (3). For this purpose we take  $P = 1.37$  s and  $L_{\text{lim}} = 2.0 \times 10^{40}$  erg s $^{-1}$  (where we apply a bolometric correction of factor 2 to the observed mean luminosity in the high state). This gives immediately a magnetar-like magnetic field of  $B = (1.1 \pm 0.4) \times 10^{14}$  G, which exceeds by a factor of 15 the largest measured so far magnetic field in an accreting X-ray pulsar (Yamamoto et al. 2013). The error on  $B$  comes from the uncertainty in a combination of factors  $k^{7/2} M_{1.4}^{-2/3} R_6^5$  in relation (3) as well as from a 50 per cent uncertainty in determination of the limiting luminosity (as a consequence of a finite width of the luminosity distribution in “high” state) and the bolometric correction. For example, if instead of using an averaged luminosity in high state as the limiting one we take the minimal observed in this state ( $1.2 \times 10^{40}$  erg s $^{-1}$ ), the magnetic field strength would be  $B = 8.5 \times 10^{13}$  G.

The reliability of this method is illustrated by Fig. 3, where we show the correlation between the combination  $L_{\text{lim}} P^{7/3}$  and the magnetic field strength for one accreting millisecond pulsar SAX J1808.4–3658 and three X-ray pul-

<sup>3</sup> See <http://swift.gsfc.nasa.gov/results/transients/LMCX-4/>. Daily averaged count rates were translated into the source luminosity using its broadband spectrum (see, e.g., Tsygankov & Lutovinov 2005). The obtained luminosity distribution was shifted by a factor of 20 to visually match the M82 X-2 luminosity range.



**Figure 3.** The observed correlation between the magnetic field strength  $B$  and a combination of the limiting luminosity at the start of the propeller regime and the period,  $L_{\text{lim}} P^{7/3}$ , for four pulsars is shown by circles with error bars. The dashed line represents the theoretical dependence from equation (3) assuming standard parameters  $M = 1.4M_{\odot}$ ,  $R = 10$  km,  $k = 0.5$ . The star indicates the position of the ULX M82 X-2 for which we estimate  $L_{\text{lim}} P^{7/3} = 5 \times 10^{40}$  erg s $^{4/3}$ , that corresponds to the  $B$ -field strength of  $1.2 \times 10^{14}$  G.

sars GRO J1744-28, 4U 0115+63, and V 0332+53 where the action of the propeller was mentioned in the literature (see Appendix A). This sample consists only of sources with the confidently determined nature of the compact object as a neutron star with a sufficiently strong magnetic field, i.e. sources with the pronounced X-ray pulsations. We see that the data spread over four orders of magnitude in  $B$  are well described by a theoretical dependence given by equation (3) and shown by the dashed line in Fig. 3.

#### 4 CONCLUSION

In spite of a number of suggestions for the presence of magnetars in binary systems (Shakura 1975; Bozzo et al. 2008; Doroshenko et al. 2010; Reig et al. 2012; Klus et al. 2014), no such systems up to date have been unambiguously identified. Here we show that the ULX M82 X-2 regularly enters the “propeller regime” of accretion which is seen as dramatic variations of the emitted luminosity and two well-defined peaks separated by a factor of 40 in the X-ray luminosity distribution. These observations imply the dipole component of the neutron star magnetic field of  $\sim 10^{14}$  G, making the source the first confirmed accreting magnetar.

Our discovery of such a strong magnetic field in a pulsar-ULX naturally explains the observed deficit of ULXs powered by accretion onto a neutron star. For instance, binary population synthesis models suggest (Shao & Li 2015) neutron star-ULX to be not less numerous than black hole-ULX. Moreover, the observed binary parameters (Bachetti et al. 2014) of M82 X-2 (donor mass  $M_c > 5.2M_{\odot}$  and orbital period  $\sim 2.5$  d) are shown to be typical. However, these studies do not account for an extreme narrowness of all physical parameters permitting for such a binary to operate as ULX (Mushtukov et al. 2015). Namely, the magnetic

field strength should be high enough to make the scattering cross-section small in order to support super-Eddington luminosity from the accretion column. Furthermore, for a high accretion rate needed for a neutron star to become ULX, the magnetic field should be high enough to make magnetosphere larger than the spherization radius (where the accretion disc scale-height becomes comparable to the distance from the neutron star), otherwise the accreting material will be blown away by radiation and the accretion may proceed only in a nearly spherically-symmetric fashion, which is limited by the Eddington luminosity (Mushtukov et al. 2015). This naturally limits the magnetic field of pulsar-ULXs to be greater than  $\sim 3 \times 10^{13}$  G.

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## APPENDIX A: OBSERVATIONAL EVIDENCE OF THE ONSET OF THE PROPELLER REGIME

For Fig. 3 we have collected all the cases of X-ray pulsars where the action of the propeller was mentioned in the literature. We selected only sources with the confidently determined nature of the compact object as a neutron star with a sufficiently strong magnetic field, i.e. sources with the pronounced X-ray pulsations.

The first discovered accreting millisecond pulsar SAX J1808.4–3658 has the shortest spin period of  $P = 2.5$  ms and the lowest magnetic field strength among sources in the sample determined to be  $B = (0.8 \pm 0.5) \times 10^8 k^{-7/4}$  G

(Ibragimov & Poutanen 2009). Substituting  $k = 0.5$  (as we do in our work) the final magnetic field strength on the neutron star shown in Fig. 3 is  $B = (2.7 \pm 1.7) \times 10^8$  G. Variations in the flux by a factor of 100 have been observed by the *Swift* observatory during the 2005 outburst and interpreted as the transition to the propeller regime of accretion (Campana et al. 2008). The luminosity at the onset of propeller in the 0.3–10 keV energy range was estimated to be  $L = (3 \pm 1) \times 10^{35}$  erg s $^{-1}$  assuming a source distance of 3.5 kpc (Galloway & Cumming 2006). Applying a bolometric correction of factor 1.7 we get  $L_{\text{lim}} = (5 \pm 2) \times 10^{35}$  erg s $^{-1}$ .

An intermediate X-ray pulsar GRO J1744–28 situated 1° from the Galactic centre has the pulse period of 0.467 s and the magnetic field  $B \approx 5.3 \times 10^{11}$  G determined from the cyclotron absorption line at  $E_{\text{cyc}} \approx 4.7$  keV (D’Ai et al. 2015; Doroshenko et al. 2015). Because this feature originates from the vicinity of the neutron star surface, its energy was corrected for the gravitational redshift to be compared to the magnetic field of SAX J1808.4–3658. The disappearing of strong pulsations from the source during the decay of 1996 outburst when the 2–60 keV flux was in the range  $F = (4 \pm 2) \times 10^{-9}$  erg cm $^{-2}$  s $^{-1}$  was interpreted as the onset of the propeller regime (Cui 1997). Assuming a distance to the source of 8 kpc (Giles et al. 1996), the propeller threshold luminosity can be estimated as  $L_{\text{lim}} = (3.0 \pm 1.5) \times 10^{37}$  erg s $^{-1}$ .

The propeller effect was observed also in two well-studied transient X-ray pulsars with Be companions – 4U 0115+63 and V 0332+53, characterized by the spin periods of 3.6 s and 4.35 s and the magnetic fields of  $B \approx 1.3 \times 10^{12}$  G (White et al. 1983) and  $3.0 \times 10^{12}$  G (Makishima et al. 1990), respectively. The sudden decrease of the flux of 4U 0115+63 and its pulsed fraction below the luminosity  $L_{\text{lim}} = (1 \pm 0.5) \times 10^{35}$  erg s $^{-1}$  can be interpreted as the onset of the propeller (Campana et al. 2001). In the case of V 0332+53, the minimum flux in the 1–15 keV range measured just before the turnoff was  $F = (3 \pm 1) \times 10^{-10}$  erg cm $^{-2}$  s $^{-1}$  (Stella et al. 1986). Taking the distance to the source of 7 kpc (Negueruela et al. 1999) and applying the bolometric correction of factor 1.5 we get  $L_{\text{lim}} = (2.6 \pm 0.9) \times 10^{36}$  erg s $^{-1}$ . We use a 10 per cent uncertainty in the magnetic field strength for the three pulsars, because of the uncertainty in the redshift correction and in the measured energy of the cyclotron line.

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